KLOTZ & MILES

The Effect of Fillets on the Strength of Cast Iron Machine Parts

Mechanical Engineering

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THE EFFECT OF FILLETS

ON THE STRENGTH OF CAST IRON MACHINE PARTS

BY

HARRY JOHN KLOTZ
AND
PAUL KEITER MILES

THESIS

FOR THE

DEGREE OF BACHELOR OF SCIENCE

IN

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THIS IS TO CERTIFY THAT THE THESIS PREPARED UNDER MY SUPERVISION BY

Harry John Klotz and Paul Keiter Miles

ENTITLED The Effect of Fillets on the Strength of Cast Iron Machine Parts

IS APPROVED BY ME AS FULFILLING THIS PART OF THE REQUIREMENTS FOR THE

DEGREE OF Bachelor of Science in Mechanical Engineering.

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I

INTRODUCTION.

The fact that the strength of pieces made of cast iron is increased by means of filleting the corners is generally known. But as far as a quantitative expression of the relation between the dimensions of the section and theradius of the fillet is concerned, no information has been available to guide designers. As was discovered when this investigation was under contemplation, information on the subject is very meager.

The lack of tests on this subject may be explained by two facts. First, as is generally known, cast iron is at best a very difficult material to investigate on account of its variation in quality. The results that are obtained by experiment and in practice have been found to be so at variance with those predicted by theory that the assumptions on which the theory is based must be seriously in error.This is due, no doubt, to the irregularities in cast iron. No assurance can be had that the quality of iron in any two pieces is near enough the same to permit of an absolute comparison. In fact, experience shows that the quality of metal in different parts of a given specimen may vary considerably. The second reason for the absence of data on this subject is that designers have been content to pass over the problem without giving it due consideration. The usual practice has been to let the radius of the fillet be governed by the general proportions of the piece. Under this mode of procedure, mistakes are bound to be made, and with the extent to which cast iron is used in present day machine construction, it is readily seen that definite knowledge on the subject is really of considerable import-

ance.

It was to secure definite information which will help in deciding on the radius of the fillet that should be used in a given case, that this investigation was undertaken. The writers realized that any results obtained would be of greater qualitative than quantitative value, because of the nature of the material under investigation. The attempt was made to attack the problem from as nearly a practical standpoint as possible, as will be shown under the description of test pieces. It was the belief of the writers that the tests planned would lead to some experimental basis for selecting the proper size of fillet.

II

TEST PIECES

The character of the specimen which it was decided to use is shown by Fig. 1 on the following page. The specimen was so designed that while the radius of the fillet might be varied, the depth of the section through the fillet and the moment arm of the applied force about that section would be kept constant. It was imperative that these two factors be maintained constant, in order that the results obtained from specimens with different radii of fillets could be compared and the effect of the fillets shown directly. The piece was designed by the straight beam formula in ordinary use, to break at a load of 10,000 pounds, as this load was a convenient one to handle on the testing machine at the disposal of the writers. It is believed that this test piece is more or less representative of conditions found in actual practice. It was recognized that cast iron is seldom used where subjected to pure tension. However, many cast

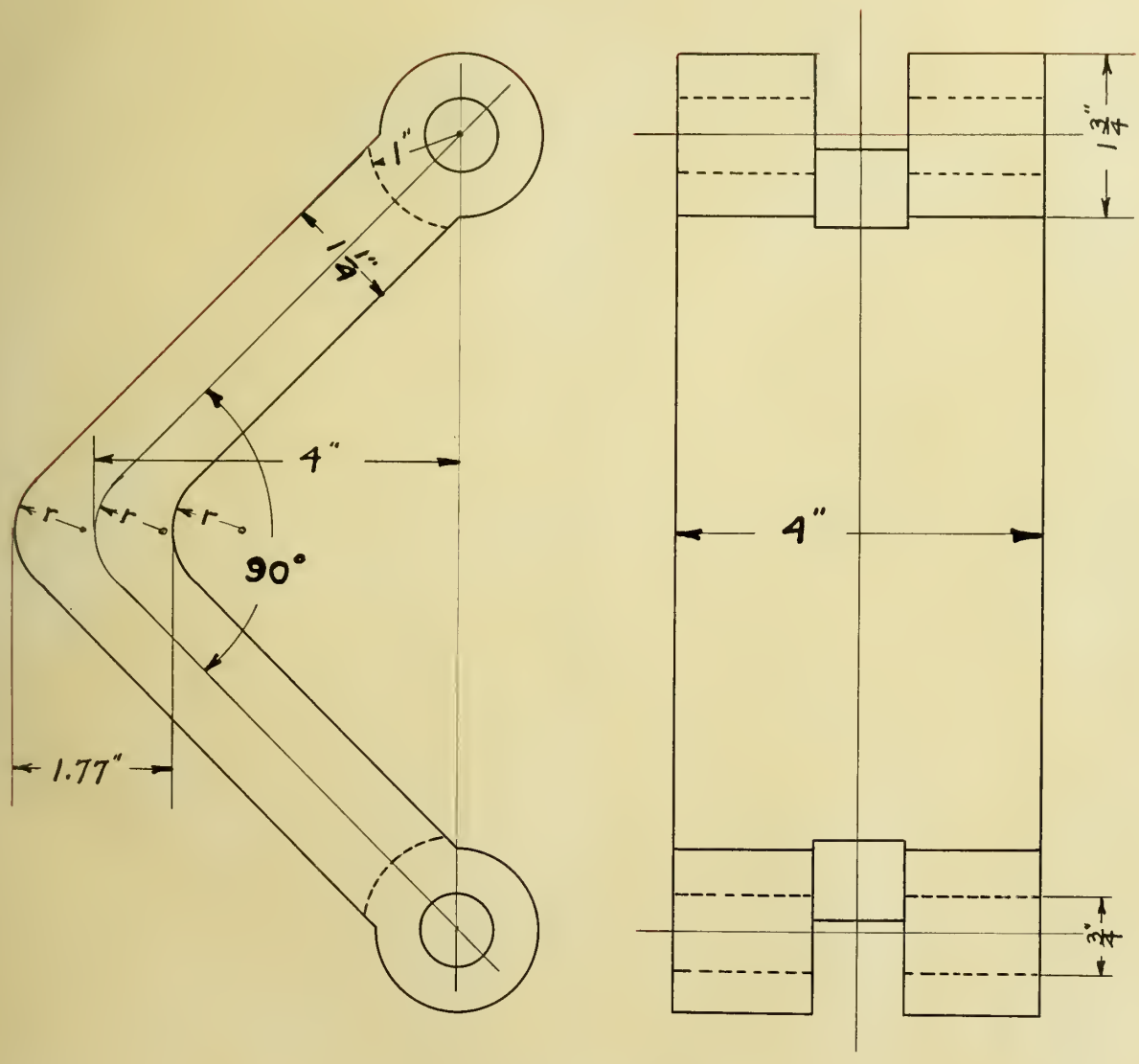

Fig. 1

Test Piece for

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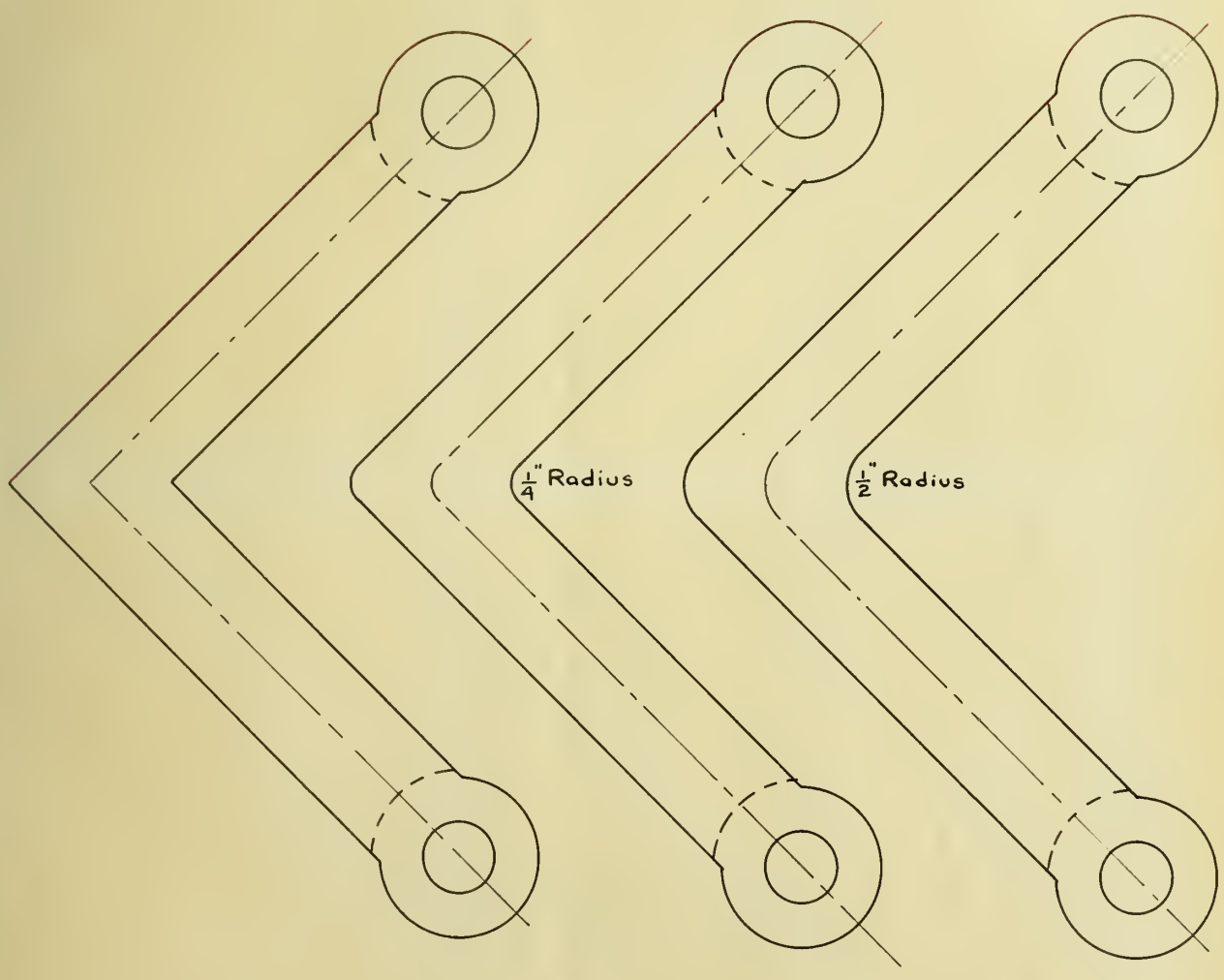
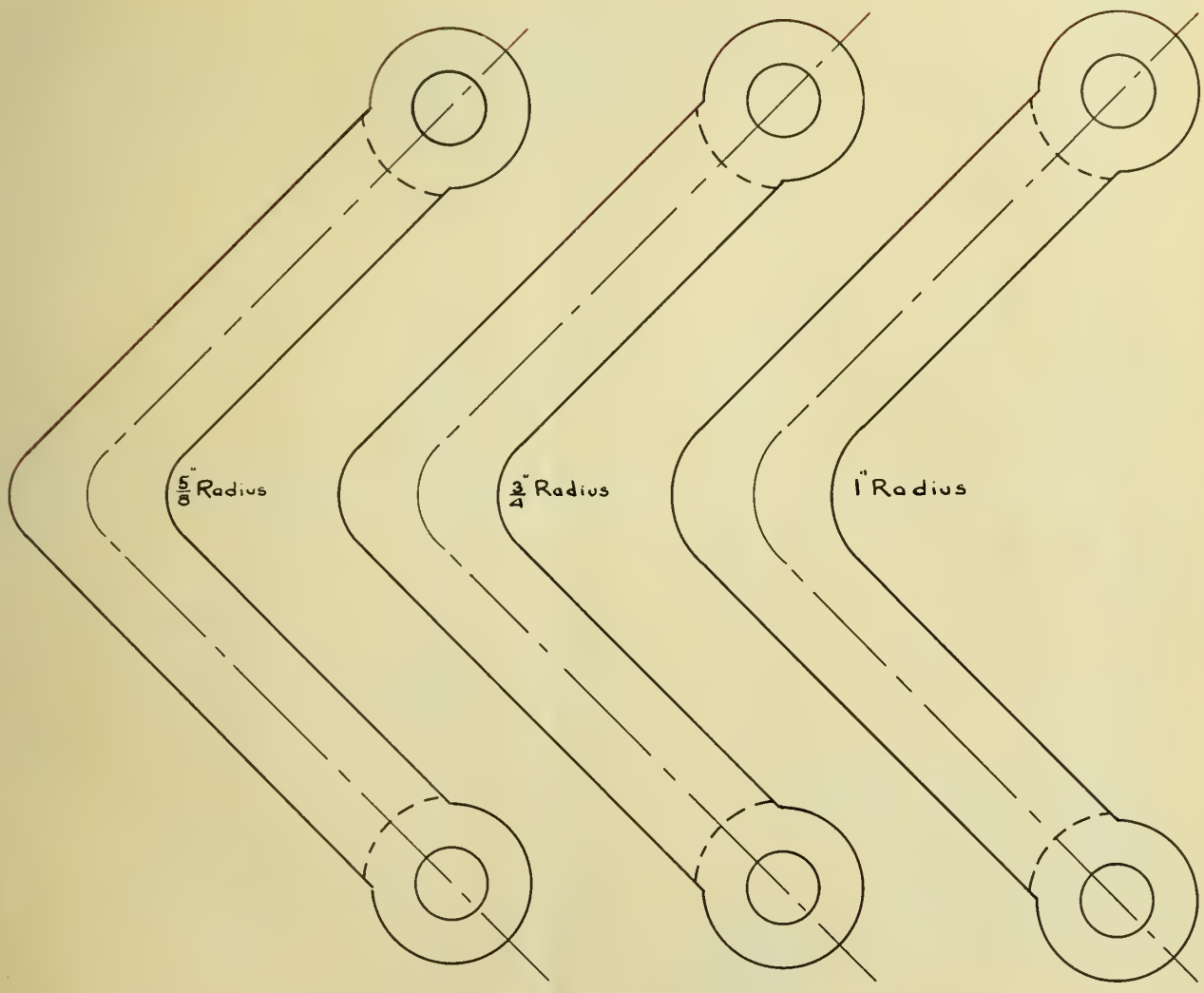


Test Pieces

Scale - Half size

Thesis of Klotz and Miles



TEST PIECES

Scale - Half size

Thesis of Klotz and Miles

iron machine parts are required to withstand combined bending and tensile stress, especially when the bending stress is large in proportion to the direct stress.

It was believed that the curved beam theory of Bach could be applied to this specimen, and the results of the tests compared with those predicted both by this theory and by the straight beam theory in ordinary use. A brief treatment of Bach's theory and its application to this specimen will be included in the discussion of the results.

In order that test pieces might be secured which would be strictly accurate and which would meet the requirements, the writers themselves did the shop work involved. This consisted in making the patterns and core boxes, and in making the cores and setting up the molds in the foundry. All of this work was performed in the shops of the Mechanical Engineering Department of the University.

Realizing that the value of the results obtained would depend very largely upon the uniformity of the quality of iron in all specimens, it was the desire of the writers to have all the test pieces for the final tests cast from the same heat and, if possible, from the same run of iron. These conditions, however, were not obtained as will be explained later.

In setting up the molds the writers were very careful to treat every mold in as nearly the same manner as possible. All the ramming was done by one man who was careful to ram them all the same amount. As the castings for the preliminary tests did not peel as well as was desired, and as was necessary for securing the required accuracy in machining the pieces, a sea-coal facing was used on the molds for the test pieces used in the final series of tests. The pouring of the molds was superintended by the writers as a

further precaution.

The metal used was a rather better than average quality of grey iron, a large amount of scrap being used in the heats from which the pieces were poured. The quality of iron obtained from the different heats was essentially the same, care being taken by those in charge of the foundry to insure this fact. The castings were all well rattled to clean them and facilitate their handling in the machine shop. It was necessary to treat them all the same in this respect, as rattling is known to increase the strength of castings.

In the machine shop the holes were drilled for receiving the pins which held the eye bars used in gripping the pieces in the testing machine. These holes were carefully laid out so that the line of action of the applied force would be just four inches from the center of gravity of the filleted section. Not only was the exact location of these holes important, but it was also necessary that they be drilled parallel to the center line of the section through which the break was expected to occur. Care was taken in clamping the pieces to the drill table to see that this condition would be obtained. The pins and eye bars for holding the specimens in the testing machine were made of high carbon steel and were case-hardened. The hole in the eye bar was so drilled that the pin would be a snug fit in the test piece and have a slight amount of play in the eye bar.

III

PRELIMINARY TESTS

As a means of obtaining some clue as to what results might be expected and to aid in mapping out the method of procedure for the final tests, a short series of preliminary tests was made. For these tests, four different sizes of fillets were used, namely+ fillets of zero radius, i.e., a sharp corner, one-quarter, one-half, and one inch radii. The effort was made to secure two or more specimens of each size but, due to faulty molds or mishaps in pouring, only one each of the quarter and half inch radii were obtained. In this series the load was applied at a uniform rate till rupture occurred, only the breaking load being recorded, in addition to the manner of breaking and the nature of the fracture.

As to the manner of applying the load, it should be noted that the pins which held the eye bars were fitted in the specimens fairly tightly, while the fit of the pins in the eye bars was just sufficient to allow free turning of the bar about the pin. This reduced the friction of the pins to a minimum, thus preventing this source from causing any appreciable error by shifting the action line of the applied force and thus varying its moment arm. Care was taken to secure the pieces in the testing machine so that the line of pull would be perpendicular to the transverse plane of symmetry of the piece. This was essential in order that the required four inch moment arm would be secured.

In all the tests a Riehle , one hundred thousand pound, vertical, two-screw testing machine was used. The cross-head of the machine was run at a speed of about one-tenth inch per minute.

The results of these tests were, in general, what was ex-

pected, and indicated that further tests were warranted. In the case of the sharp cornered specimens and the one of one-quarter inch radius, the instant of breaking could be determined only by the dropping of the scale beam, so slow and quiet was the rupture. In the cases of the half inch and one inch radii the breaks were sudden, accompanied by loud reports. In all cases the line of fracture on both the inside and outside of the piece was a straight line of remarkable sharpness.

The feature which was strongly brought out by these preliminary tests and which was perhaps of greatest interest , was the fact that the specimen with the fillet of one-half inch radius was the last to break in the fillet itself. That is, in the sharp cornered and the quarter and half inch radii specimens, the line of fracture started from the inside corner or center of the fillet, and proceeded across the section, as shown in the drawings on the data sheet. But in the cases of the specimens having fillets of one inch radius, the fracture occurred in the straight part of the piece, approximately at the point of tangency of the fillet with the straight side of the piece. This result showed that the desirable size of fillet for a piece of these proportions was somewhere between one-half inch and one inch radius, since any further increase caused the break to occur in the straight part of the piece closer to the line of action of the applied force. Because of this discovery, it was decided to include specimens with fillets of five-eighths and three-quarters inch radii in the final tests.

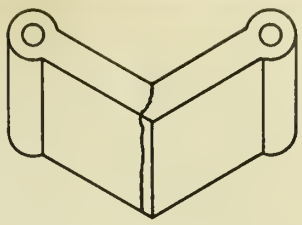
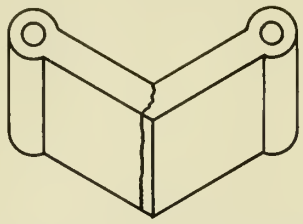
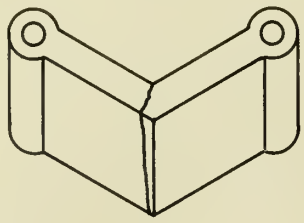
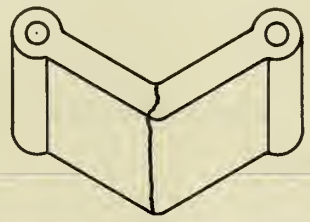
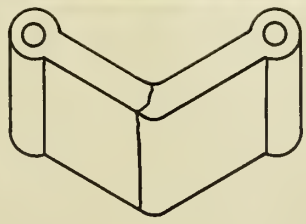
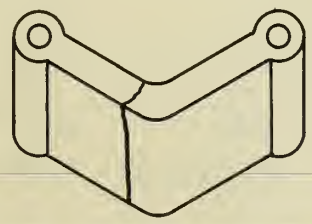
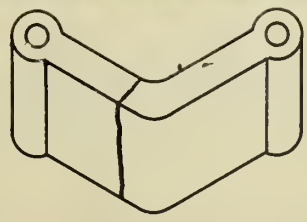
The results of the preliminary tests showed that the strength of the specimen was increased with each increase in the size of the fillet, although no definite relation between the strength

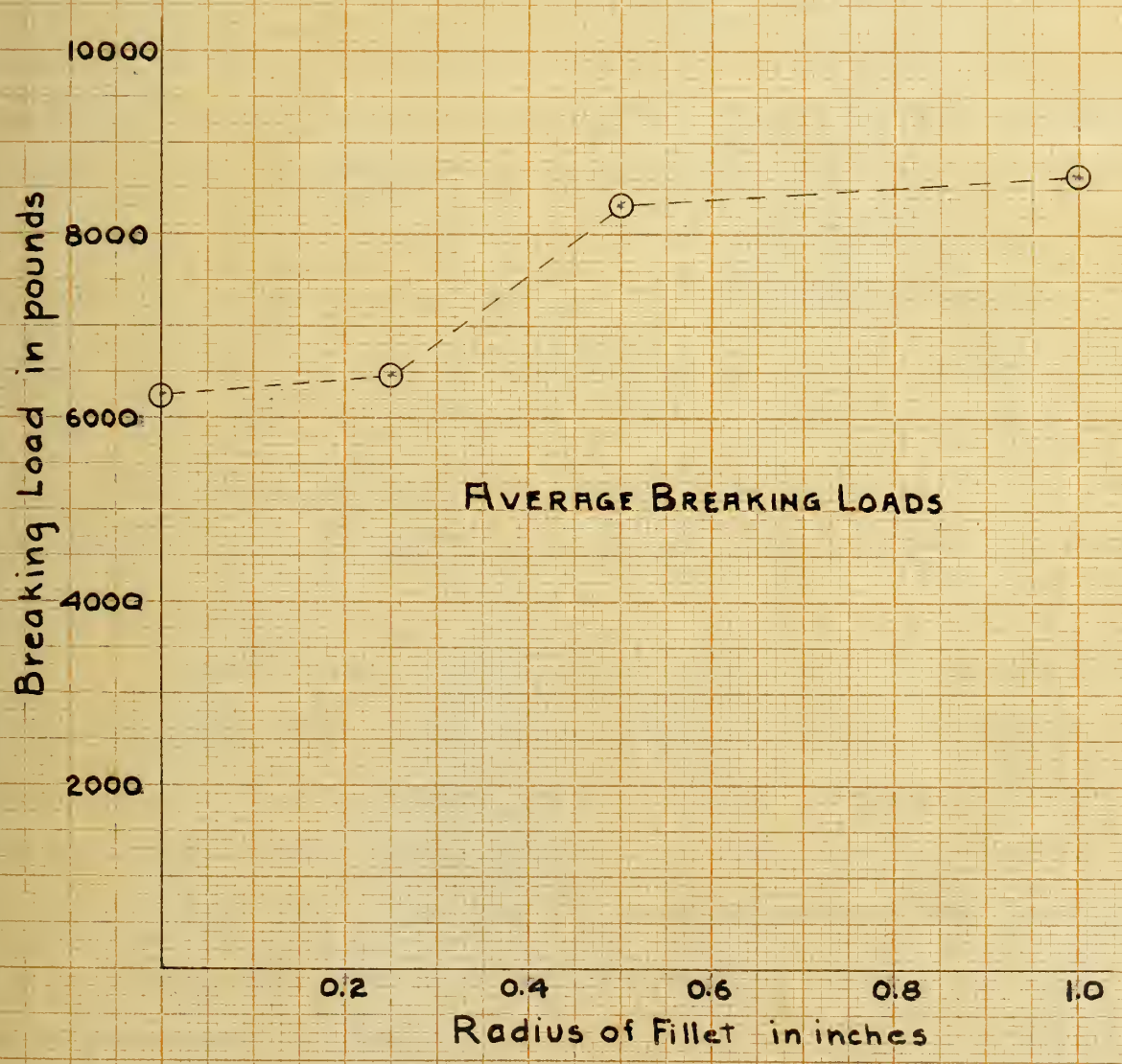
and the size of the fillet could be derived from the testing of so few specimens.

The quality of iron in the specimens was found to be quite uniform. One flaw appeared consistently in each specimen. This was a spongy spot which occurred in the same place in each specimen, namely, at about the middle of the depth and closer to the inside than to the outside edge. The reason for its occurrence is easily explained. The section at the corner is the largest in the piece, contains the most metal, and consequently is the last part of the casting to cool. This causes all the impurities to collect at this point forming the spongy mass. This condition may be expected in all cast iron under similar circumstances unless a riser can be put in at this point to obviate the difficulty at the time of casting.

The effect of the fillets on the crystalline structure of the iron was distinctly shown at the fractures. In the sharp cornered specimens, the structure of the iron was very markedly flaky around the outside and inside edges and extending well toward the center of the section. As the fillets were introduced and their radii increased, this flaky structure became less and less apparent and the iron appeared more as a homogeneous mass.

Results of Preliminary Tests

No.	Radius of Fillet	Thickness	Depth	Moment Arm	Breaking Load	Remarks
1	0	1.85"	4.00"	4.00"	7215	 Slow break No noise. Spongy spot at about center of depth and near inside edge.
2	0	1.77"	3.99"	4.03"	5720	 No noise to indicate failure of specimen. Usual spongy spot.
3	0	1.81"	4.00"	4.00"	5930	 Quiet break. Usual spongy spot
4	1/4"	1.79"	3.97"	4.09"	6480	 Quiet break. Usual spongy spot. One small blowhole
5	1/2"	1.80"	3.98"	4.09"	8320	 Sudden break Moderate report. Usual spongy spot.
6	1"	1.78"	4.00"	3.95"	8510	 Sudden break. Distinct report. Spongy spot not evident. Rupture at point of tangency of inside radius.
7	1"	1.80"	3.95"	4.09"	8800	 Loud report. No spongy spot. 2 small blowholes. Rupture through straight section.



Results of Preliminary Tests
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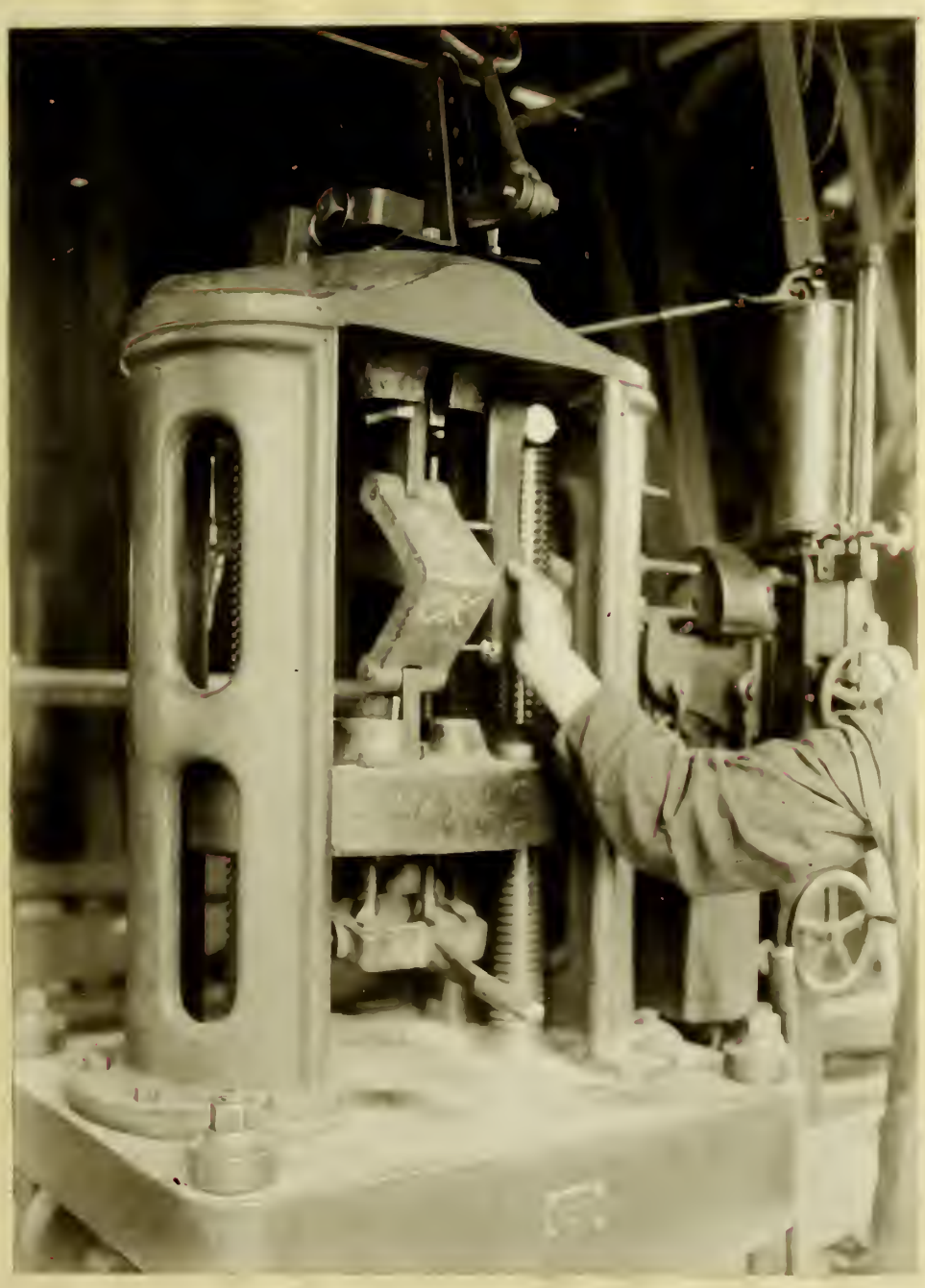
IV

FINAL TESTS

The specimens for the final series of tests were of six sizes, having fillets of zero, one-quarter, one-half, five-eighths, three-quarters, and one inch radii. Four specimens of each size were tested, thus making a total of twenty-four tests. In two of the sizes it was possible to make five tests, due to a few extra castings being supplied. It was thought that it would be of interest to determine the effect of the fillets on the deflection of the pieces. For this purpose a Berry type removable extensometer was used. Two small holes were drilled in each specimen six inches apart and on a line parallel to the line of pull, to be used in attaching the extensometer to the piece. The load was increased by increments of five hundred pounds in some cases and one thousand in others, extensometer readings being taken after each increase. The manner of gripping the test pieces in the machine and of attaching the extensometer is clearly shown in the photograph on page

Due to defective castings resulting from the first heat, the test pieces were taken in all from four heats. The number of perfect castings from each heat was as follows: fourteen from the first, six from the second, and four from each the third and fourth. The quality of the iron in the first three heats was found not to vary much, if any, more than from different parts of the same heat. The iron from the fourth heat was softer, due to more pig being used instead of so much scrap.But the number of pieces taken from this heat was so small as not to influence average results seriously.

The results obtained agreed quite closely with those of the preliminary tests. As before, the sharp-cornered specimens failed



Photograph showing specimen in machine
and method of attaching extensometer.

Thesis of Klotz and Miles.

noiselessly, while the breaking of the pieces with the one-quarter inch fillet was accompanied with a dull and scarcely audible snap. All the other specimens failed suddenly and with a loud report. The manner of failure of the sharp cornered specimens bears out the curved beam theory for curvatures of very small radius, that is, pieces bent at right angles on themselves. In pieces of this kind the neutral fiber passes through the inside edge of the sharp corner and, hence, no resistance to bending can be offered. Therefore, the slightest bending strain produces incipient rupture. Actually this condition does not exist because the stress distribution is so modified as to shift the neutral axis from its theoretical position. The character of the break, however, indicates that this condition is approached.

The variability of cast iron is clearly shown by the results obtained. In some cases the breaking load of two specimens of the same dimensions differed as much as two thousand pounds. The curve, page 44, plotted between the breaking loads and the radii of the fillets, shows graphically the effect of the increased radius of fillet on the strength of the piece. All but two of the sizes are seen to lie practically on a straight line. For the one-half inch radius the result is seen to be especially discordant, the variations in the loads at which the specimens of this size broke being unusually extreme. This was due to the exceptionally poor quality of the iron in the pieces of this size, blowholes of unusual size appearing in several of the specimens.

In the case of the fillet of five-eighths inch radius, the ideal condition of having all the specimens cast from the same heat, was obtained. As would consequently be expected, these specimens exhibited the least variation in breaking load between the

several pieces. Even in this case, a maximum variation of a trifle more than on thousand pounds was observed.

The use of the extensometer furnished some interesting results. The manner in which the general trend of the deflection in the various pieces coincides is strongly brought out by the deflection curves. It will be noticed that the graphs are typical for cast iron, being curves whose curvature increases as rupture is approached. This indicates that for even moderate loads cast iron does not closely follow Hook's law.

The curves plotted from the average deflections at various loads for the different radii show, as might be expected, that the deflection at a given load decreases as strength of the section is increased by increasing the radius of the fillet. Furthermore, the decrease in deflection due to the increased size of fillet is more marked at the higher loads. The quality of the iron accounts for the irregularities in these curves corresponding to those in the curves of average breaking loads.

V

THEORETICAL DISCUSSION

It was deemed of considerable interest to investigate this problem on the basis of the theory of the curved beam. For this purpose the "Theory of Stresses in Curved Bars" in Appendix A of Bulletin No. 18 of the University of Illinois Engineering Experiment Station was applied to the problem in hand. This theory is substantially that laid down by Bach in his "Elasticitat und Festigkeit", Article 54.

An expression for the intensity of stress at any point

of the section,

$$S = \frac{P}{f} + \frac{M_b}{fr} + \frac{M_b}{zfr} \times \frac{Y}{r+Y}$$

is obtained from this theory, in which,

P = the external force, in pounds, acting at right angles to the section

f = the area of the section in square inches

M_b = the moment of the couple acting at the section

The value of M_b is positive when it tends to increase the curvature of the bar, and negative when it tends to decrease its curvature.

y = the distance, in inches, from the neutral axis of the section to the point under consideration, and is positive when measured toward the convex side of the bar and negative when measured toward the concave side, that is, toward the center of curvature

For a rectangular cross section of width "b" and depth "2a", according to Bach,

$$Z = -1 + \frac{r}{2a} \log_e \frac{1 + \frac{a}{r}}{1 - \frac{a}{r}}$$

in which "r" equals the radius of curvature of the neutral axis of the section.

It was discovered that this theory could be applied to only one radius of fillet, namely, the one inch, as the center of curvature of the neutral axis of each of the other radii fell within the section itself. Evidently, this makes the value of "a" greater than "r", in which case it is impossible to evaluate "z" and hence to apply the theory.

For the fillet of one inch radius,

$$Z = -1 + \frac{1}{1.8} \log_e \frac{1+0.9}{1-0.9} = -1 + \frac{2.94}{1.8} = 0.632$$

In this case, P = 9930 lb., M_b = - 9930 x 4 = - 39720 lb. in., and y = - 0.9 in. Hence,

$$s = \frac{9930}{4 \times 1.8} - \frac{39720}{4 \times 1.8} - \frac{-39720}{0.632 \times 4 \times 1.8} \times \frac{-0.9}{1 - 0.9}$$

$$= 1380 - 5520 + 78500$$

$$= 74360 \text{ lb. per sq. in.}$$

As the modulus of rupture of cast iron in flexure is known to be in the neighborhood of 35000 lb. per sq. in., the extreme stress which is obtained above by the application of Bach's curved beam theory indicates that the pieces under investigation and the manner in which they were stressed, did not conform to the conditions upon which this theory is based.

For the purpose of comparison, the straight beam theory was also applied, which gives an expression for the maximum stress, "s", as follows:

$$s = \frac{P}{f} + \frac{Mc}{I}$$

In the case of the one inch fillet, this expression gives for the value of "s":

$$s = \frac{9930}{7.2} + \frac{39720}{2.16}$$

$$= 19760 \text{ lb. per sq. in.}$$

This value is seen to be about half of the expected modulus of rupture. Hence, the results obtained from the applications of the curved beam and straight beam theories point to the conclusion that the conditions in this test place the piece under investigation somewhere between these two extremes. This conclusion is a logical one and the

results obtained bear the relations to each other that might be expected, considering the peculiarities of the test piece which separate it distinctly from both the classes of straight and curved beams. The fact that cast iron does not follow Hooke's law even approximately accounts for the failure of the results obtained to substantiate the theory.

VI

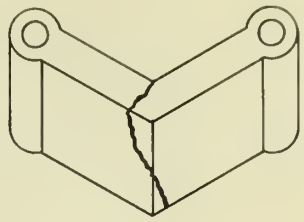
CONCLUSIONS

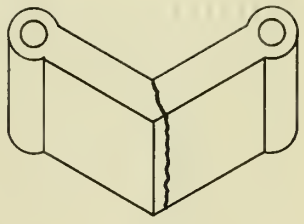
As was stated before, the writers realize that the conclusions drawn from this investigation must be largely qualitative, as it was possible to test only one size of section with varying sizes of fillets.

The curve of average breaking loads indicates that the maximum effect of the fillet was not reached and that a larger fillet would still increase the strength of the piece. However, the fact that the specimens with the one inch fillet broke through the straight part indicates that this size of fillet is large enough to make the filleted section stronger than the straight section. The size of fillet which will accomplish this result is the desirable size, beyond which it is not expedient to go.The desirable size lies between the fillets of three-quarters and one inch radius. Therefore, since the one inch size lies on the safe side, and since the thickness of the straight section is one and one-quarter inches, the ratio of the radius of the fillet to the thickness of the section is one to one and a quarter. In other words, the radius of fillet advisable for this type of piece may be taken as eight tenths of the thickness of

the section.

It is the belief of the writers that, with these results for guidance along the lines of an investigation of this nature, results could be obtained that would be a sufficient basis for quantitative conclusions. It is to be noted that the results of these tests can not be applied to pieces in which the curves of the outside and inside edges are concentric, thus making the piece of uniform thickness throughout. It would be of interest to test some specimens of this type.

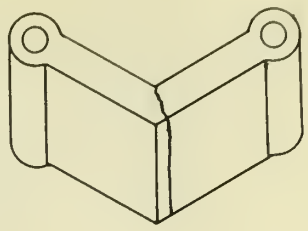
Sharp Corner Specimen No 1 Thickness 1.80" Depth 4.00" Moment Arm 4"	Load	Extensometer Reading	Deflection $\frac{1}{1000}$ inches	Remarks
	390	314		
	1100	292	22	
	1500	283	31	
	2000	277	37	
	2500	268	46	Slow break
	3070	253	61	No noise
	3950	228	86	Spongy spot $1'' \times \frac{5}{8}''$
	5010	205	109	at middle of depth
	5590	187	127	near inside edge
	5980	176	138	For total deflect-ion add .006"
	6380			

Sharp Corner Specimen No. 2 Thickness 1.81" Depth 3.93" Moment Arm 4"				
	200	463		
	660	456	7	
	1040	448	15	
	1530	437	26	
	2000	429	34	
	2540	415	48	
	3020	404	59	Slight snap
	3500	391	72	Usual spongy spot
	4000	375	88	Blow hole $1\frac{3}{8}'' \times \frac{1}{2}''$
	4620	356	107	For total deflect ion add 0.004"
	4850	322	141	
	4920			

Sharp Corner Specimen No. 4
Thickness 1.81" Depth 4.00"
Moment Arm 4"

Load	Extensometer Reading	Deflection $\frac{1}{1000}$ inches
700	234	
1050	227	7
1500	216	18
2000	207	27
2500	196	38
3000	185	49
3520	175	59
4130	163	71
4920	136	98
5320		

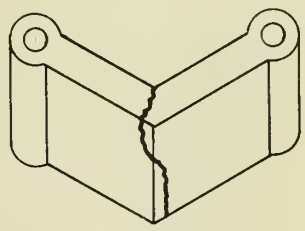
Remarks



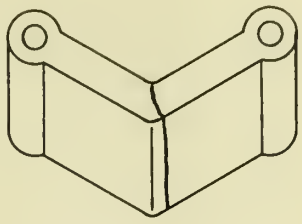
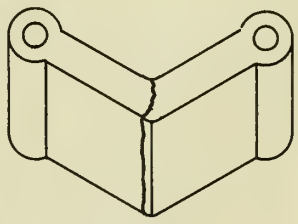
Slow break
No noise
Usual spongy spot
Small blow hole
For total deflect-ion add 0.012"

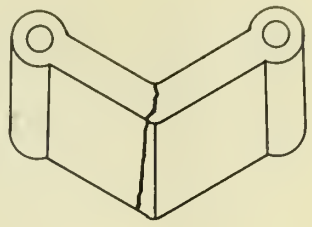
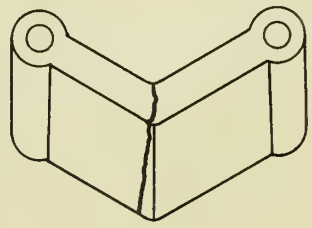
Sharp Corner Specimen No. 5
Thickness 1.80" Depth 3.93"
Moment Arm 4"

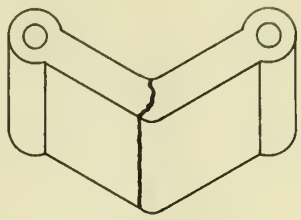
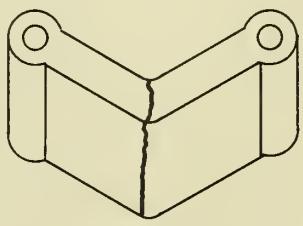
Load	Extensometer Reading	Deflection $\frac{1}{1000}$ inches
400	276	
1000	264	12
1500	225	21
2050	248	28
2590	234	42
3040	226	50
3575	217	59
4110	204	72
5040	178	98
5340	155	111
5600		

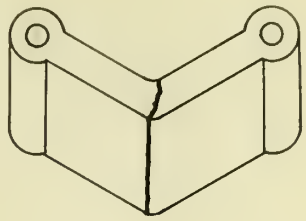
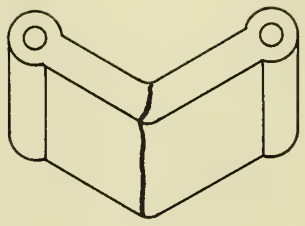


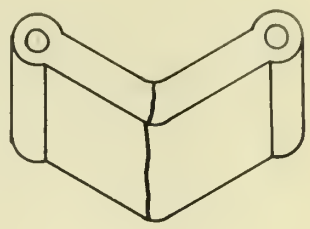
Slow break
No noise
Usual spongy spot
For total deflect-ion add 0.006"

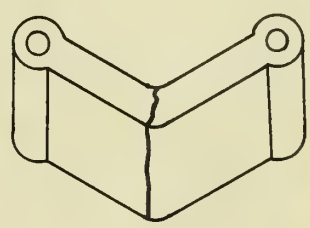
	Load	Extensometer Reading	Deflection $\frac{1}{1000}$ inches	Remarks
$\frac{1}{4}$" Radius Specimen No. 2 Thickness 1.81" Depth 3.94" Moment Arm 4"	500	287		 Sudden break Usual spongy spot $\frac{3}{8}$" × $\frac{3}{8}$" blowhole For total deflect-ion add 0.008"
	1080	271	16	
	1550	263	24	
	2080	255	32	
	2500	245	42	
	3000	237	50	
	3500	224	63	
	4130	210	77	
	4620	203	84	
	5160	184	103	
	5740			
$\frac{1}{4}$" Radius Specimen No. 1 Thickness 1.82" Depth 3.96" Moment Arm 4"	550	150		 Sudden break Usual spongy spot For total deflect-ion add 0.008"
	1000	143	7	
	1500	134	16	
	2050	125	25	
	2500	118	32	
	3000	111	39	
	3500	100	50	
	4130	85	65	
	5050	68	82	
	5950	45	105	
	6780	18	132	
	6830			

	Load	Extensometer Reading	Deflection $\frac{1}{1000}$ inches	Remarks
$\frac{1}{4}$" Radius Specimen No. 4 Thickness 1.84" Depth 4.00" Moment Arm 4"	510	178		 Sudden break. No noise. Usual spongy spot. $\frac{1}{4}$" blowhole For total deflect-ion add 0.008"
	1000	169	9	
	1500	159	19	
	2000	151	27	
	2500	142	36	
	3000	134	44	
	4000	112	66	
	4600	99	79	
	5330	79	99	
	6000	45	133	
	6100			
$\frac{1}{4}$" Radius Specimen No. 3 Thickness 1.80" Depth 3.93" Moment Arm 4"	630	260		 Sudden break Slight report Good metal ex-cept spongy spot For total deflect-ion add 0.01"
	1050	250	10	
	1500	241	19	
	2070	231	29	
	2500	223	37	
	3000	211	49	
	3500	202	58	
	4150	188	72	
	4610	177	83	
	5230	166	94	
	5970	144	116	
	7390			

	Load	Extensometer Reading	Deflection $\frac{1}{1000}$ inches	Remarks
$\frac{1}{2}$" Radius Specimen No. 2 Thickness 1.80" Depth 3.96" Moment Arm 4"	580	468		 Slow break, no report. Softer iron, smaller sponqy spot. $\frac{1}{2}$" blowhole For total deflect-ion add 0.012"
	1000	460	8	
	1500	450	18	
	2000	438	30	
	3000	417	51	
	4220	386	82	
	5000	366	102	
	5760	342	126	
	6370	318	150	
	7090	294	174	
	7800			
$\frac{1}{2}$" Radius Specimen No. 4 Thickness 1.77" Depth 4.00" Moment Arm 4"	560	334		 Dull report Usual sponqy spot. $1\frac{1}{2}$" × $\frac{1}{4}$" blow-hole. For total deflection add 0.01"
	1000	326	8	
	1500	315	19	
	2000	305	29	
	2500	293	41	
	3000	282	52	
	3500	268	66	
	4000	254	80	
	4500	241	93	
	5000	229	105	
	5500	205	129	
	5880			

	Load	Extensometer Reading	Deflection $\frac{1}{1000}$ inches	Remarks
Specimen No. 3 $\frac{1}{2}$" Radius Thickness 1.79" Depth 3.96" Moment Arm 4"	450	240		 Dull report Usual spongy spot. $\frac{3}{8}$" x $\frac{1}{8}$" blow-hole. For total deflection add 0.008"
	1000	227	13	
	1500	217	23	
	2000	210	30	
	2500	200	40	
	3500	178	62	
	4200	166	74	
	5080	146	94	
	5770	122	118	
	6700	88	152	
	6970			
Specimen No. 5 $\frac{1}{2}$" Radius Thickness 1.82" Depth 3.96" Moment Arm 4"	550	249		 Sharp report Smaller spongy spot For total deflect-ion add 0.01"
	1000	239	10	
	1500	230	19	
	2100	218	31	
	2600	209	40	
	3000	201	48	
	3500	191	58	
	4000	180	69	
	4600	168	81	
	5200	154	95	
	5940	136	113	
	7000	106	143	
	7100			

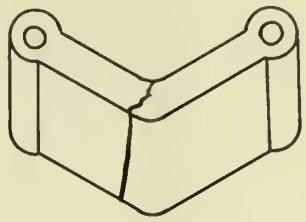
Specimen No. 2	Load	Extensometer Reading	Deflection $\frac{1}{1000}$ inches	Remarks
$\frac{5}{8}$" Radius Thickness 1.74" Depth 3.95" Moment Arm 4"	500	381		
	1000	374	7	
	1500	363	18	
	2000	355	26	
	2500	344	37	
	3500	324	57	Sharp report Size of spongy spot reduced. $\frac{1}{2}$" x $\frac{3}{8}$" blow hole For total deflection add 0.01"
	4400	305	76	
	5230	287	94	
	5810	269	112	
	6910	241	140	
	7620			

Specimen No. 1				
$\frac{5}{8}$" Radius Thickness 1.71" Depth 4.00" Moment Arm 4"	490	223		
	1000	215	8	
	1500	207	16	
	2000	195	28	
	2500	188	35	
	3000	177	46	
	3500	167	56	Sharp report Spongy spot not so evident. $\frac{3}{8}$" blowhole For total deflection add 0.01"
	4980	134	89	
	5660	116	107	
	6230	100	123	
	6890	77	146	
	7760	48	175	
	7990			

$\frac{5}{8}''$ Radius Specimen No. 4
Thickness 1.71" Depth 4.00"
Moment Arm 4"

Load	Extensometer Reading	Deflection $\frac{1}{1000}$ inches
620	238	
1110	228	10
1500	221	17
2000	212	26
3000	190	48
4000	165	73
5000	140	98
5960	111	127
7740		

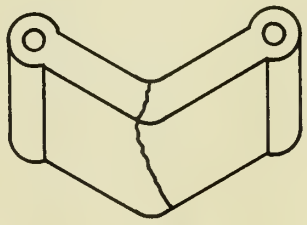
Remarks



No report, poor metal. Blowholes $1'' \times \frac{1}{4}''$ and $1\frac{1}{4}'' \times \frac{3}{8}''$. For total deflect-ion add 0.011"

$\frac{5}{8}''$ Radius Specimen No. 3
Thickness 1.72" Depth 4.00"
Moment Arm 4"

Load	Extensometer Reading	Deflection $\frac{1}{1000}$ inches
460	349	
1000	340	9
1500	332	17
2000	324	25
2500	315	34
3000	305	44
3500	296	53
4500	274	75
5690	249	100
6630	228	121
7300	208	141
8300	180	169
8660		

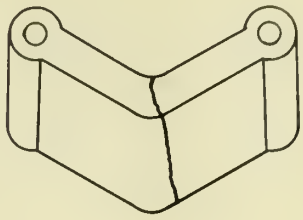


Sharp report
No blowholes
Spongy spot barely noticeable.
For total deflec-tion add 0.01"

$\frac{3}{4}$" Radius Specimen No. 3
Thickness 1.74" Depth 3.95"
Moment Arm 4"

Load	Extensometer Reading	Deflection $\frac{1}{1000}$ inches
500	422	
1000	413	9
2000	397	25
3000	378	44
4000	359	63
5070	338	84
6300	309	113
7100	282	140
8020	254	168
8090		

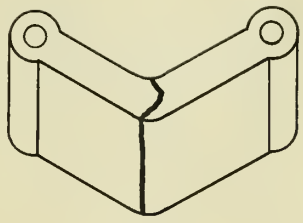
Remarks



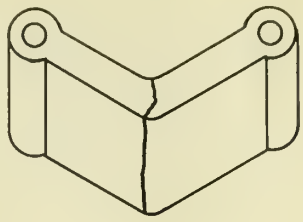
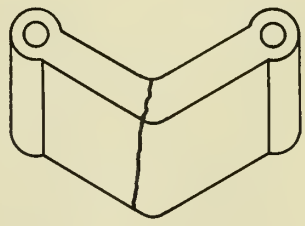
Very sudden break $\frac{5}{8}$" × $\frac{3}{8}$" in the usual spongy spot. For total deflection add 0.007"

$\frac{3}{4}$" Radius Specimen No. 2
Thickness 1.82" Depth 4.00"
Moment Arm 4"

Load	Extensometer Reading	Deflection $\frac{1}{1000}$ inches
580	251	
1000	242	9
2000	228	23
3000	210	41
4300	191	60
5140	173	78
6320	149	102
7300	126	125
8460		



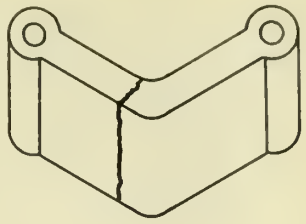
Sudden break. Sharp report. $\frac{1}{2}$" × $\frac{5}{8}$" blowhole in the usual spongy spot. For total deflection add 0.007"

	Load	Extensometer Reading	Deflection $\frac{1}{1000}$ inches	Remarks
Specim No. 1 $\frac{3}{4}$ Radius Thickness 1.80" Depth 4.00" Moment Arm 4"	500	320		
	1000	313	7	
	2000	300	20	
	3000	282	38	
	4000	264	56	Sudden break. Good metal. Spongy spot reduced in size. For total deflection add 0.008"
	5010	247	73	
	6000	228	92	
	7070	210	110	
	8140	180	140	
	9020			
Specimen No. 4 $\frac{3}{4}$" Radius Thickness 1.88" Depth 3.94" Moment Arm 4"	570	210		
	1500	200	10	
	2500	189	21	
	3500	176	34	
	4500	160	50	
	6650	123	87	
	7560	104	106	Sudden break. Good metal. Spongy spot much reduced. For total deflection add 0.006"
	8560	87	123	
	9740	61	149	
	10160			

Specimen No.1
1" Radius Depth 4.00"
Thickness 1.88"
Moment Arm 4"

Load	Extensometer Reading	Deflection $\frac{1}{1000}$ inches
510	273	
1000	266	7
1500	259	14
2500	246	27
3500	231	42
4150	222	51
5800	193	80
6430	182	91
7320	164	109
8110	149	124
8900		

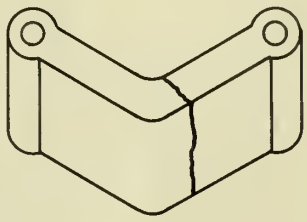
Remarks



Very quick break
Spongy spot disappeared
$\frac{1}{2}" \times \frac{1}{4}"$ blowhole
For total deflection add 0.006"

Specimen No.2
1" Radius Depth 4.00"
Thickness 1.83"
Moment Arm 4"

Load	Extensometer Reading	Deflection $\frac{1}{1000}$ inches
450	240	
1000	233	7
1500	227	13
2500	213	27
3500	199	41
4140	191	49
4920	180	60
6130	162	78
7110	142	98
8020	125	115
9750	89	151
11340	49	191
11560		

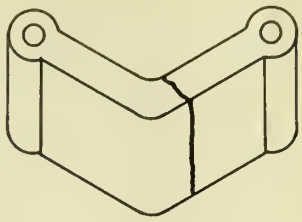


Sudden break
Very good metal
Spongy spot scarcely evident.
For total deflection add 0.006"

1" Radius Specimen No. 4
Thickness 1.84" Depth 4.00"
Moment Arm 4"

Load	Extensometer Reading	Deflection $\frac{1}{1000}$ inches
520	201	
1000	195	6
2000	181	20
3000	167	34
4000	150	51
5000	135	66
6000	117	84
7080	97	104
8040	73	128
8860		

Remarks

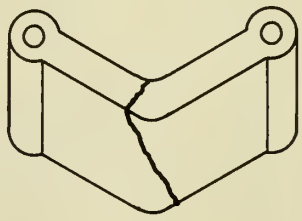


Very sudden break
Spongy spot
scarcely evident
$\frac{3}{4}" \times \frac{3}{8}"$ blowhole.
For total deflection
add 0.007"

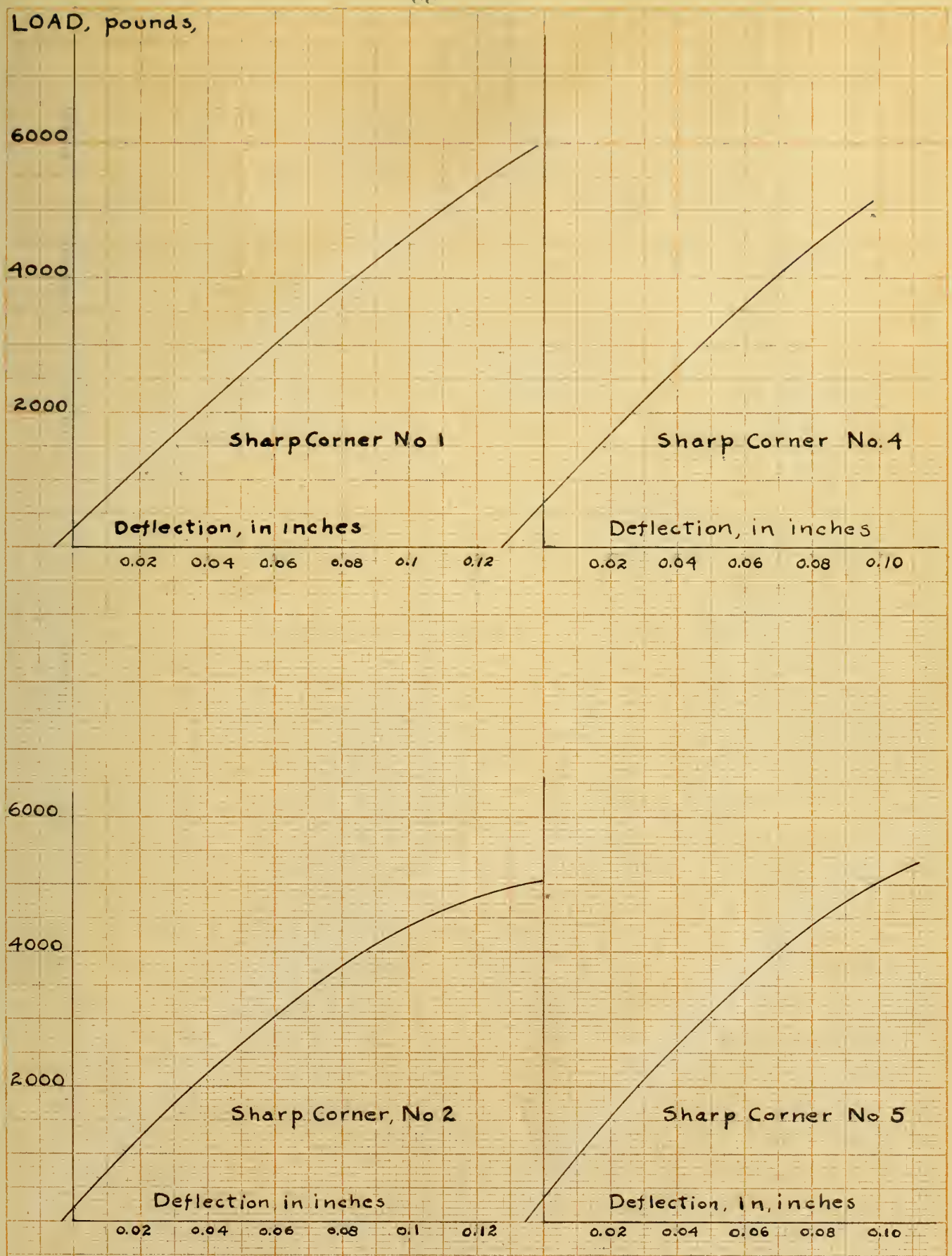
1" Radius Specimen No. 3
Thickness 1.80" Depth 3.96"
Moment Arm 4"

Load	Extensometer Reading	Deflection $\frac{1}{1000}$ inches
500	260	
1000	252	8
2000	237	23
3000	221	39
4000	204	56
5000	186	74
6000	167	93
7100	142	118
8120	120	140
9160	90	170
10390	50	210
10400		

Remarks



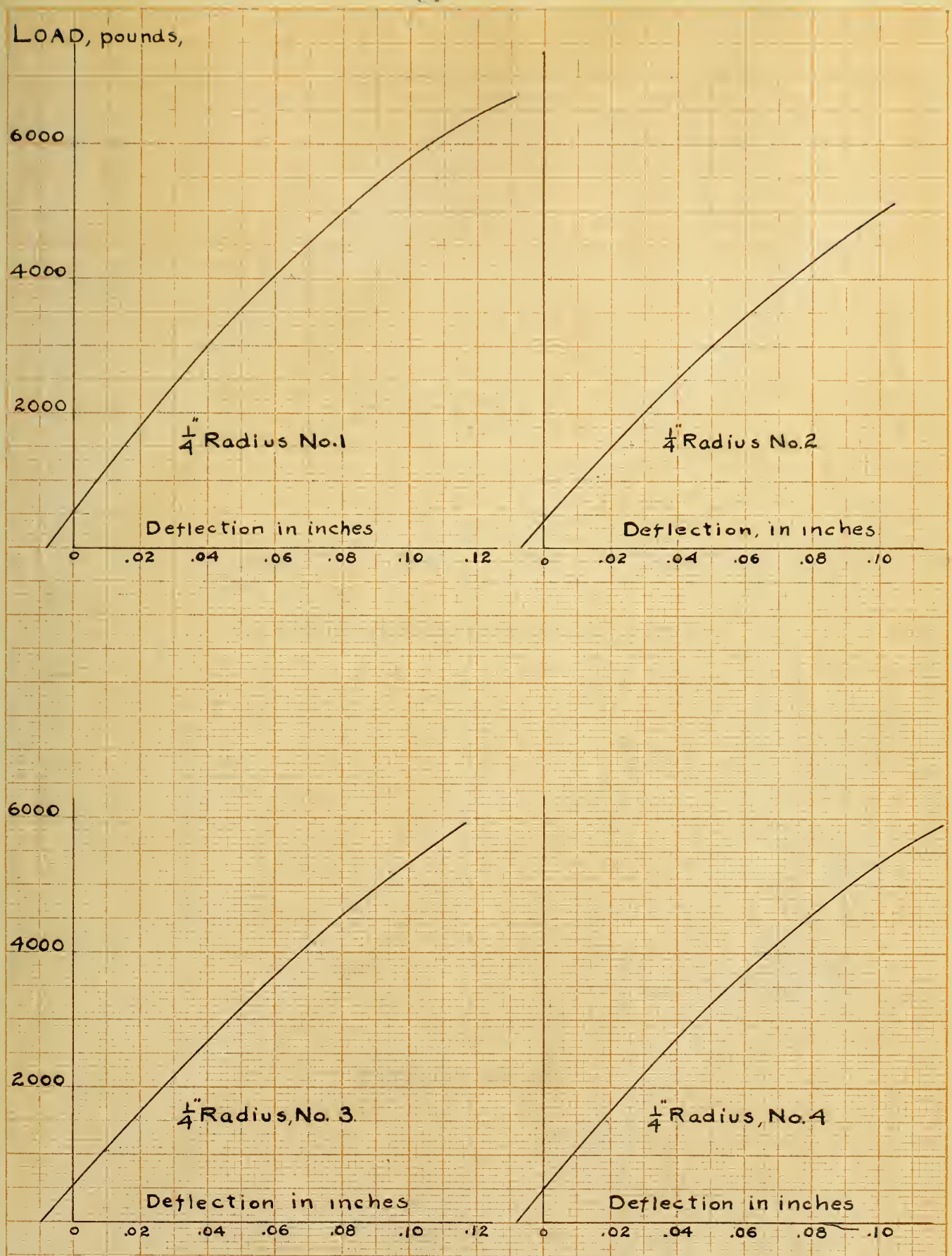
Very sudden break
Spongy spot
very small.
For total deflec-
tion add 0.008"



DEFLECTION CURVES

Thesis of Klotz and Miles

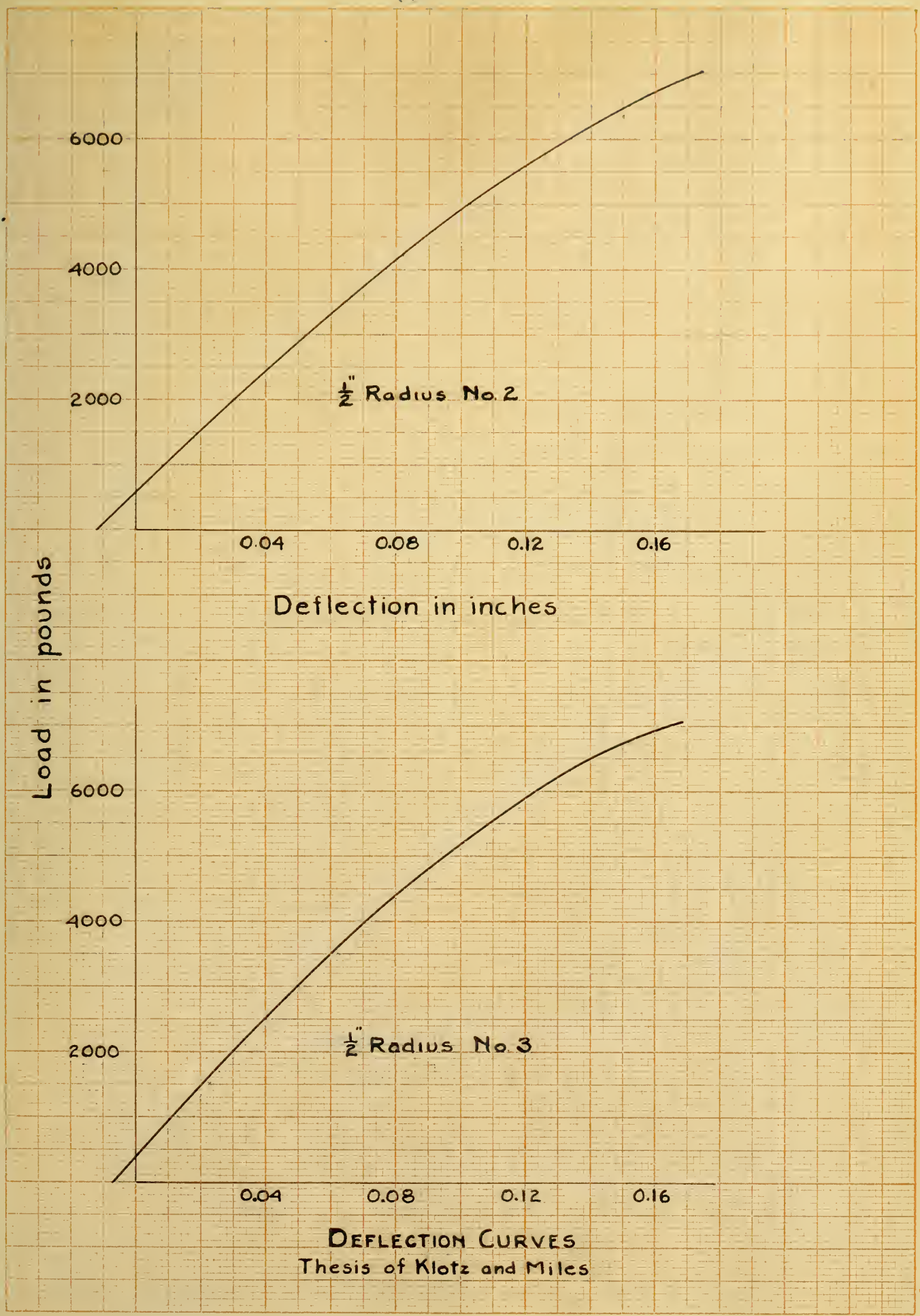
U. OF I. S. S. FORM 3



DEFLECTION CURVES

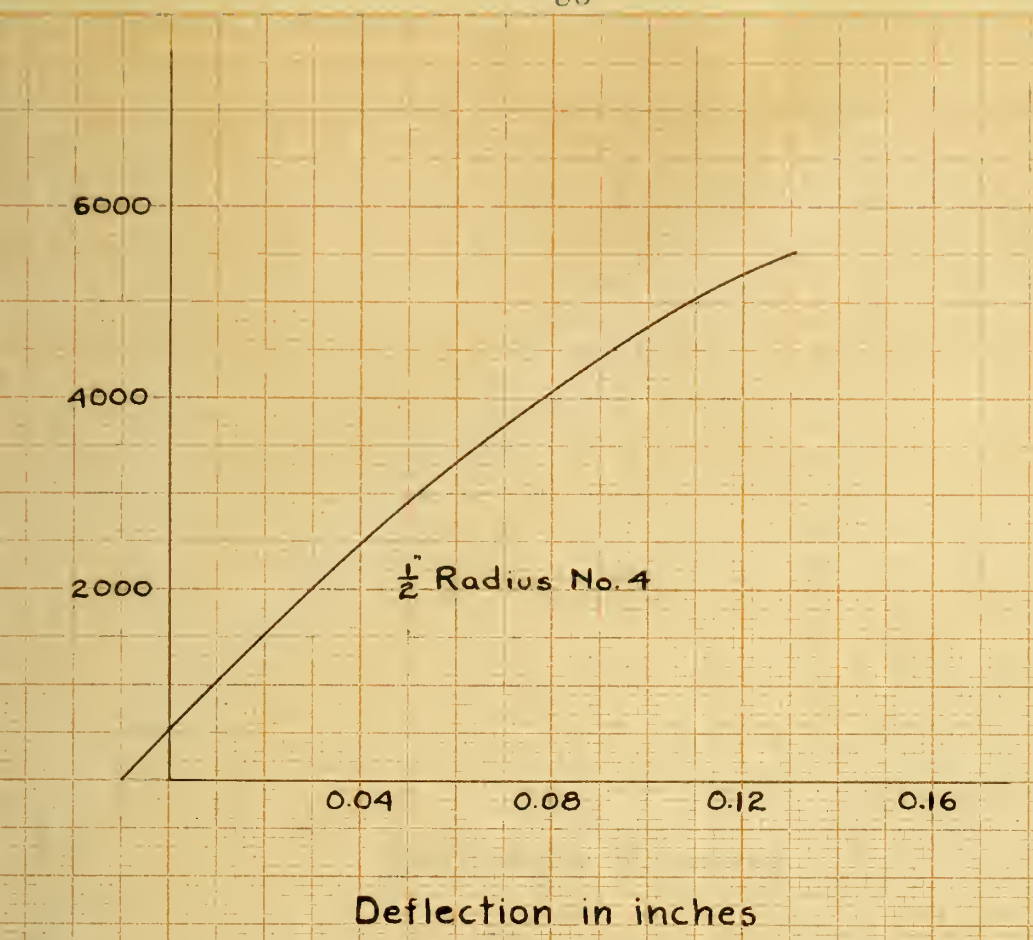
Thesis of Klotz and Miles

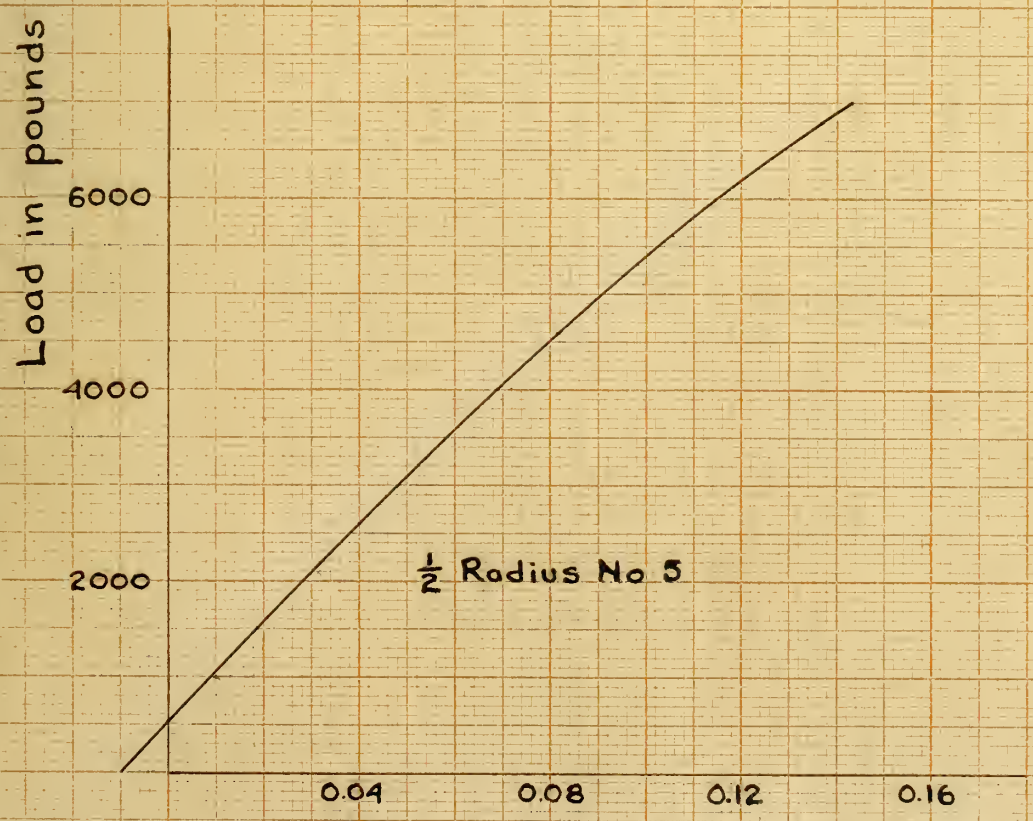
L OF I. G. S. FORM 3



DEFLECTION CURVES
Thesis of Klotz and Miles

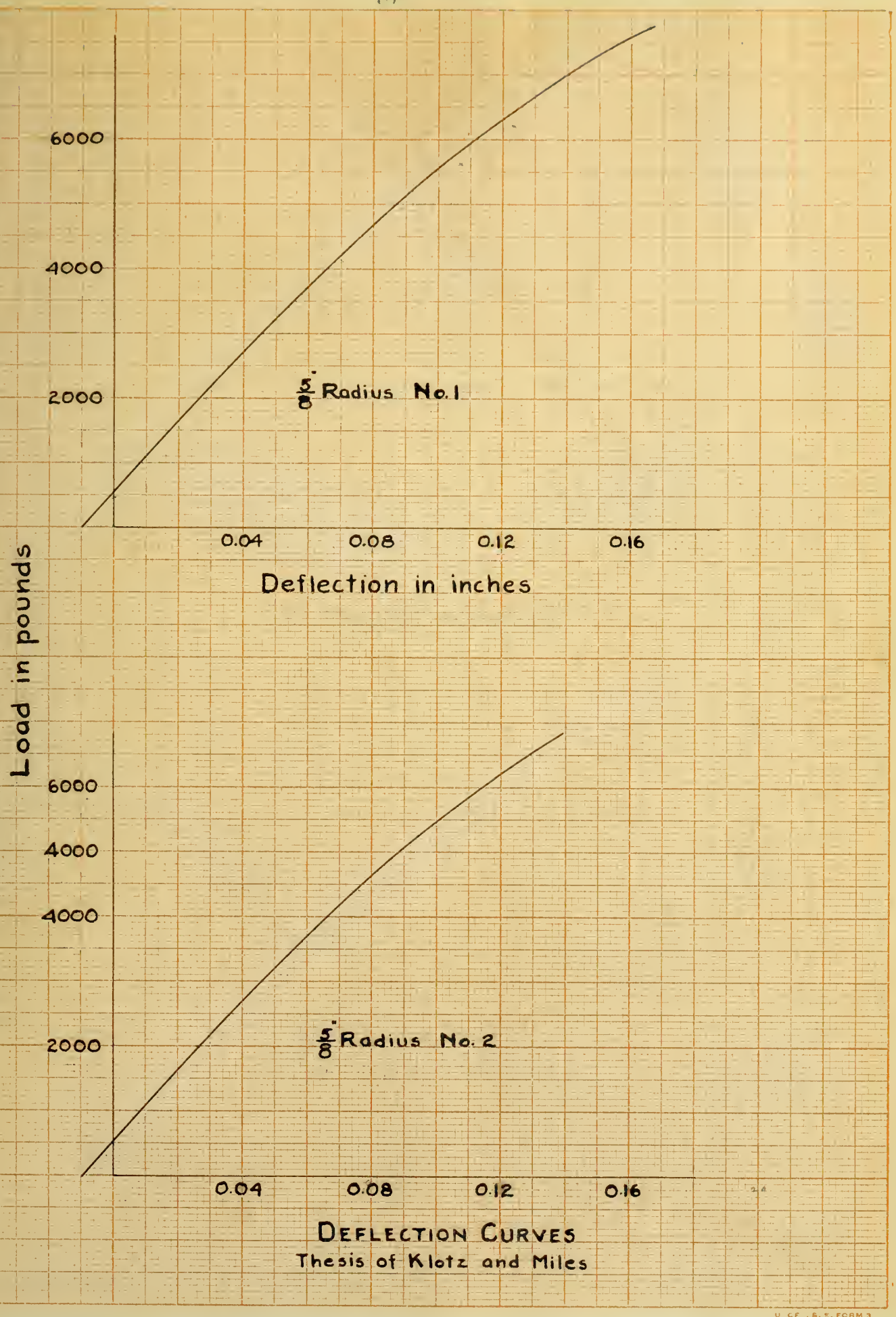
U. OF I. S. S. FORM 3



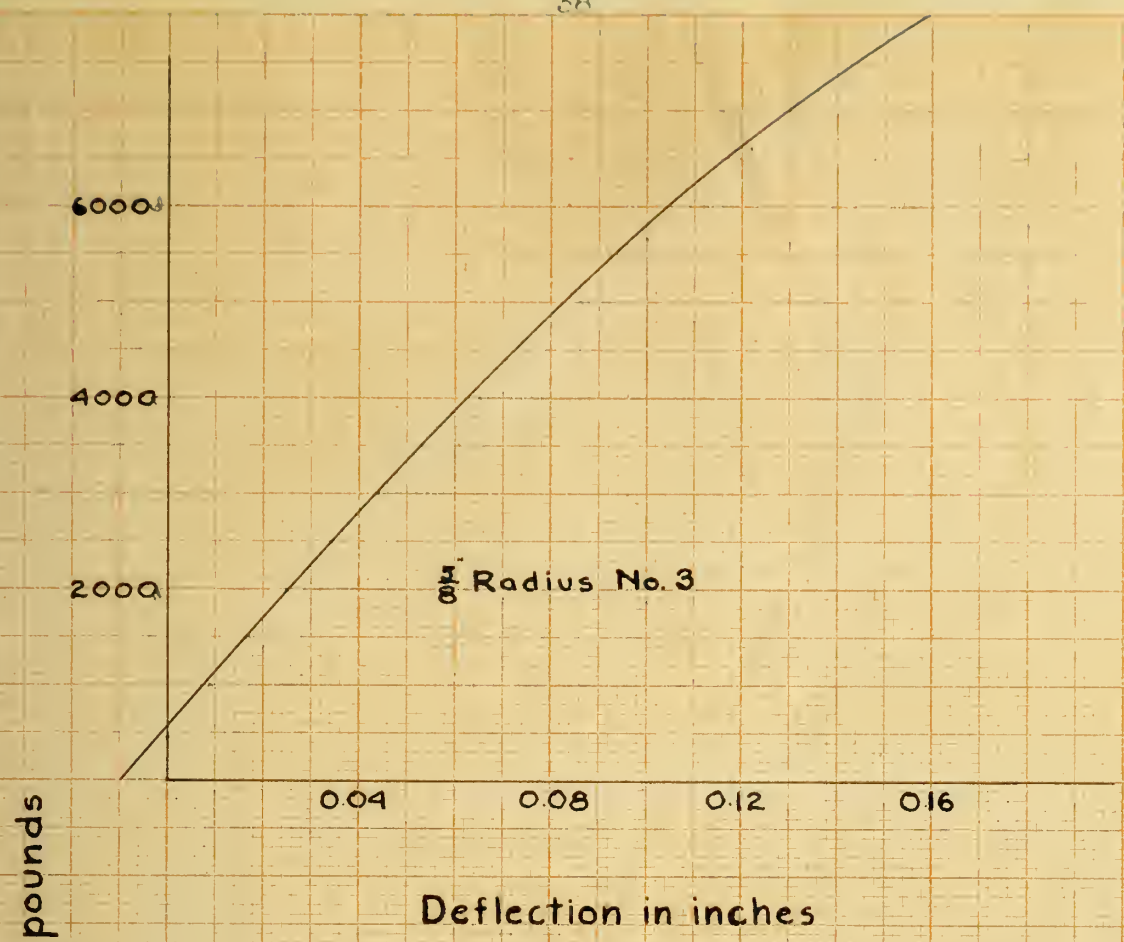


DEFLECTION CURVES
Thesis of Klotz and Miles

U OF I S. S. FORM 3

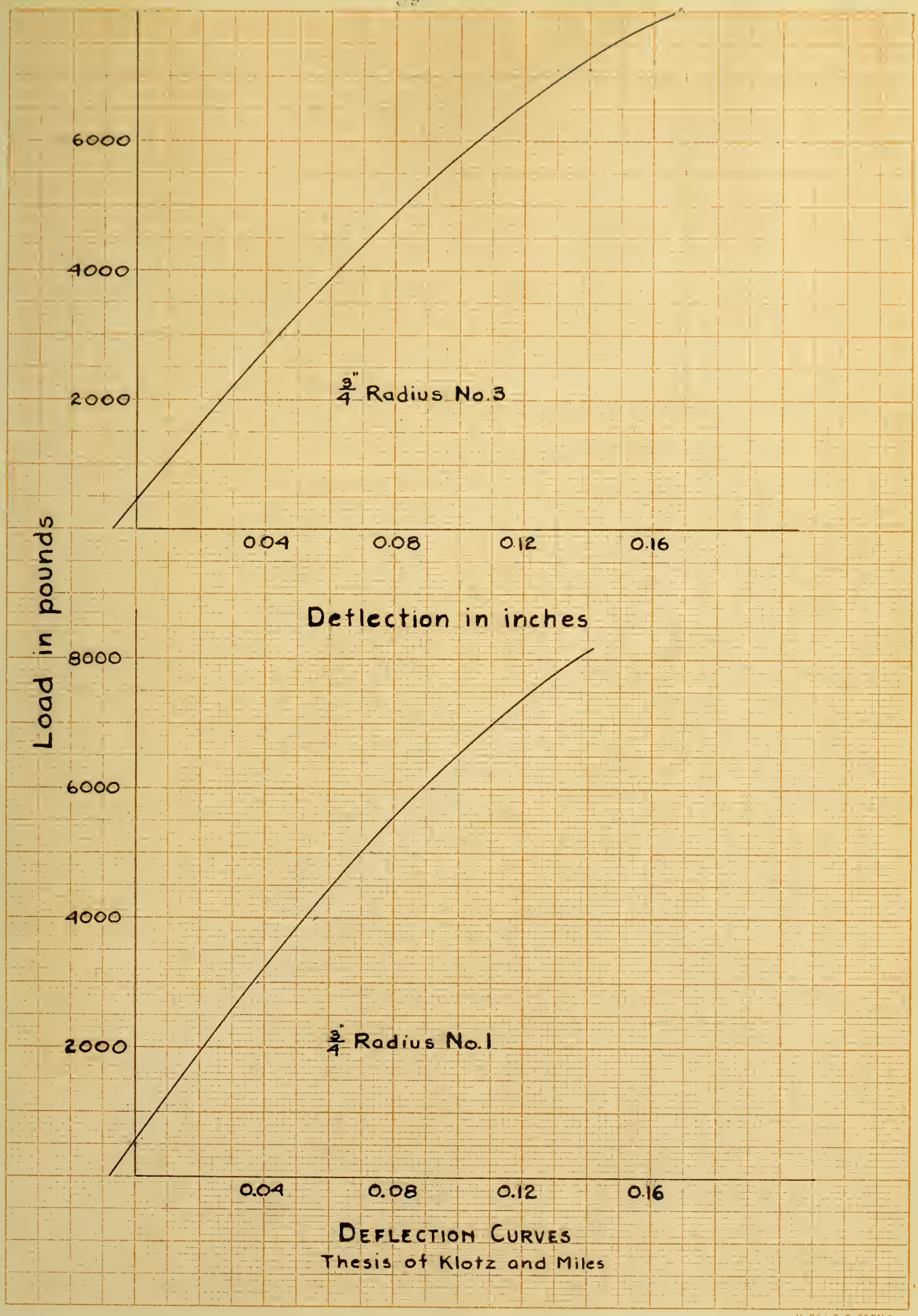


DEFLECTION CURVES
Thesis of Klotz and Miles



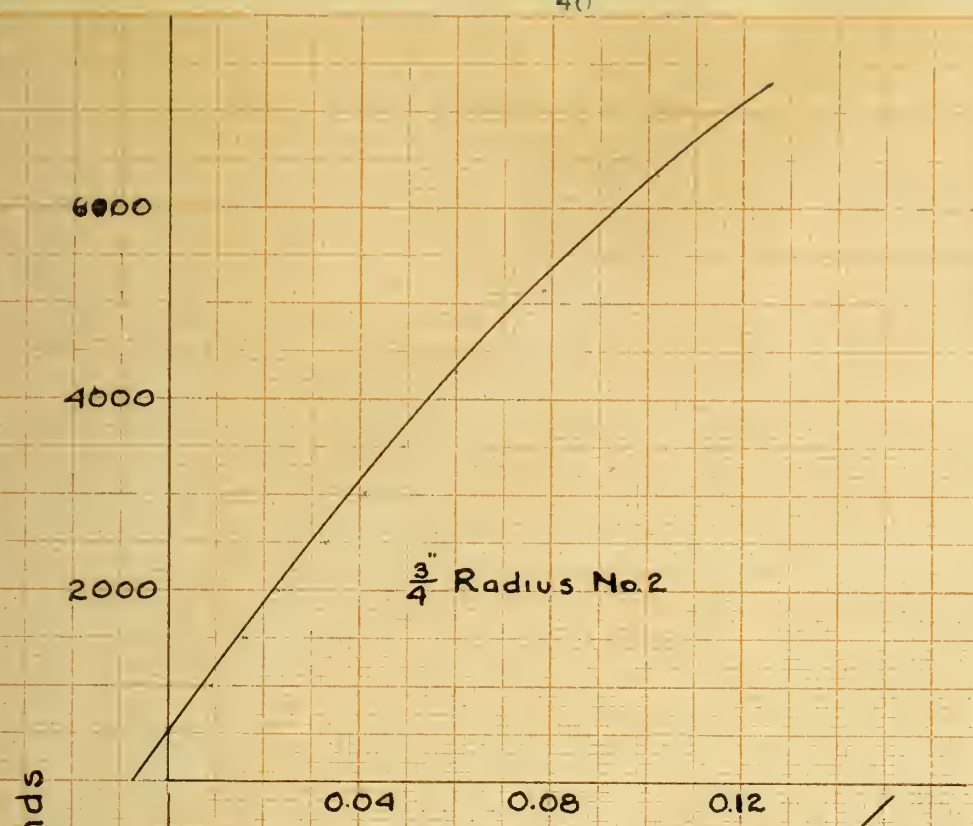
DEFLECTION CURVES
Thesis of Klotz and Miles

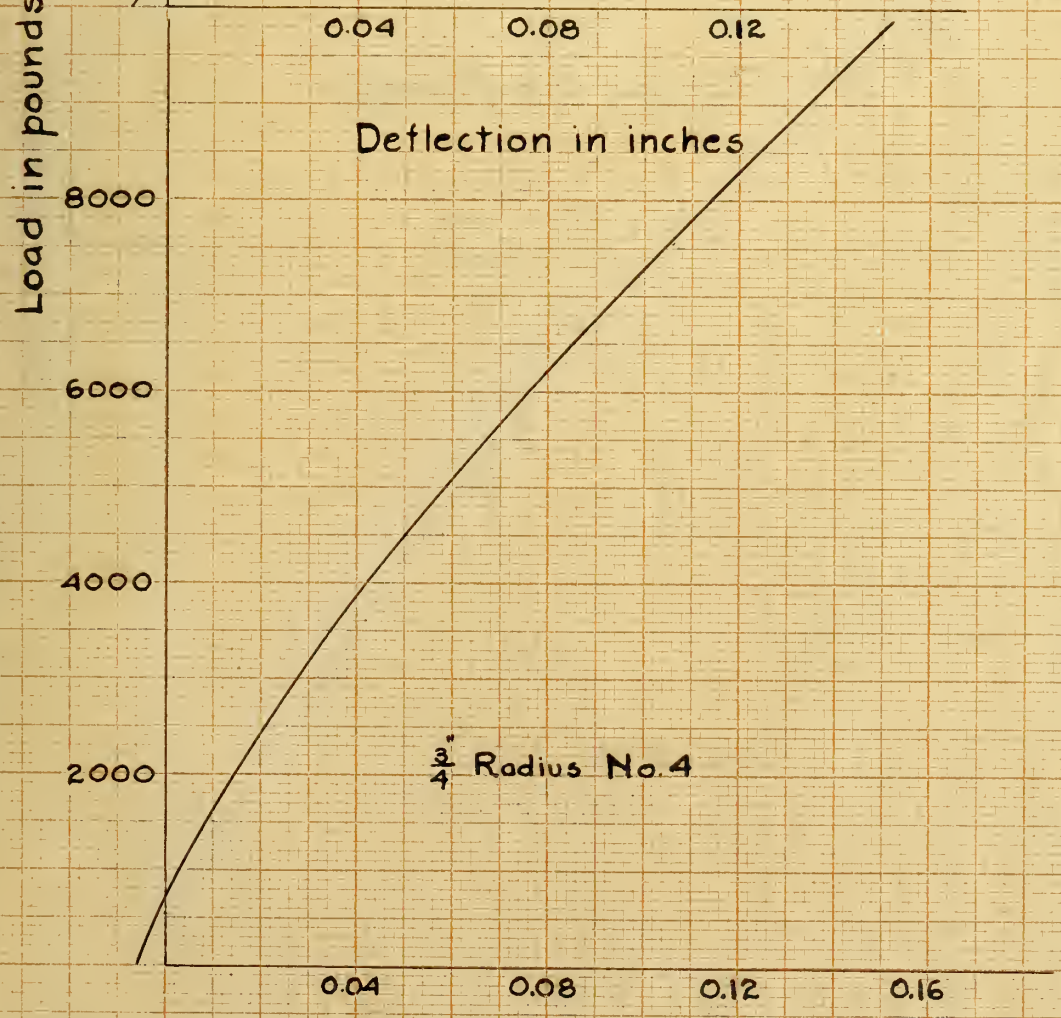
U. OF I. S. S FORM 3



DEFLECTION CURVES
Thesis of Klotz and Miles

U OF I. S. S. FORM 3





Deflection Curves

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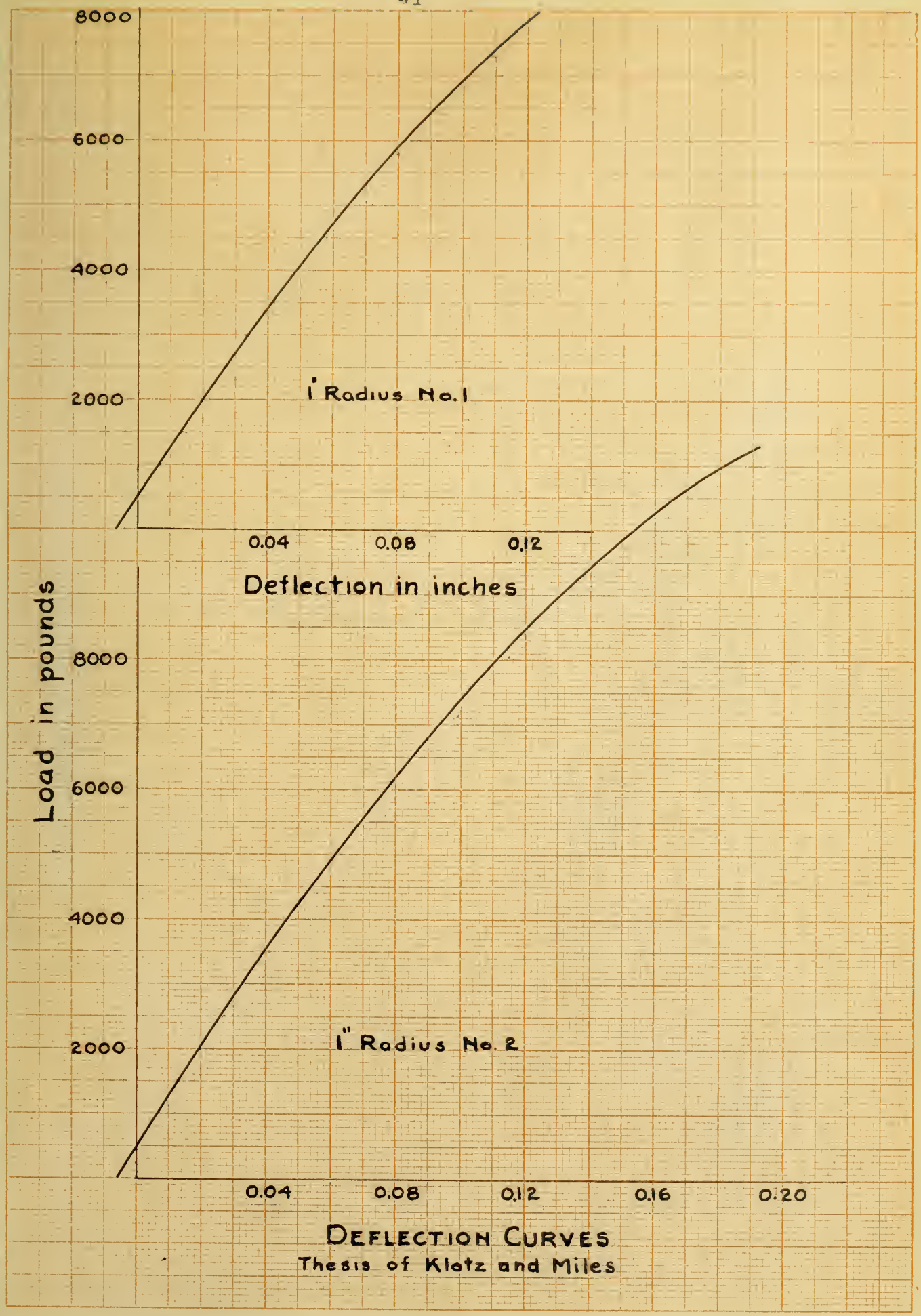

DEFLECTION CURVES
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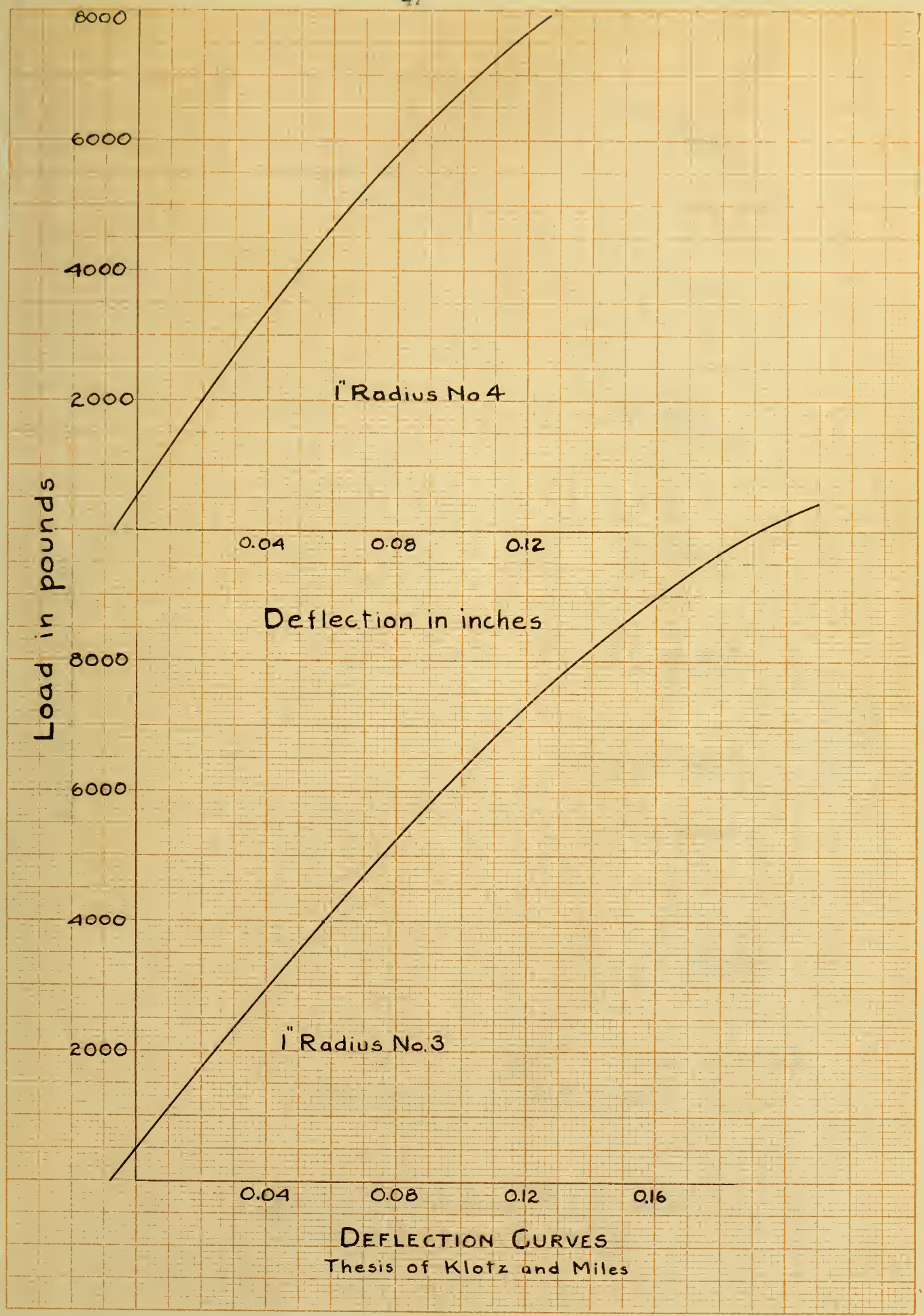

DEFLECTION CURVES
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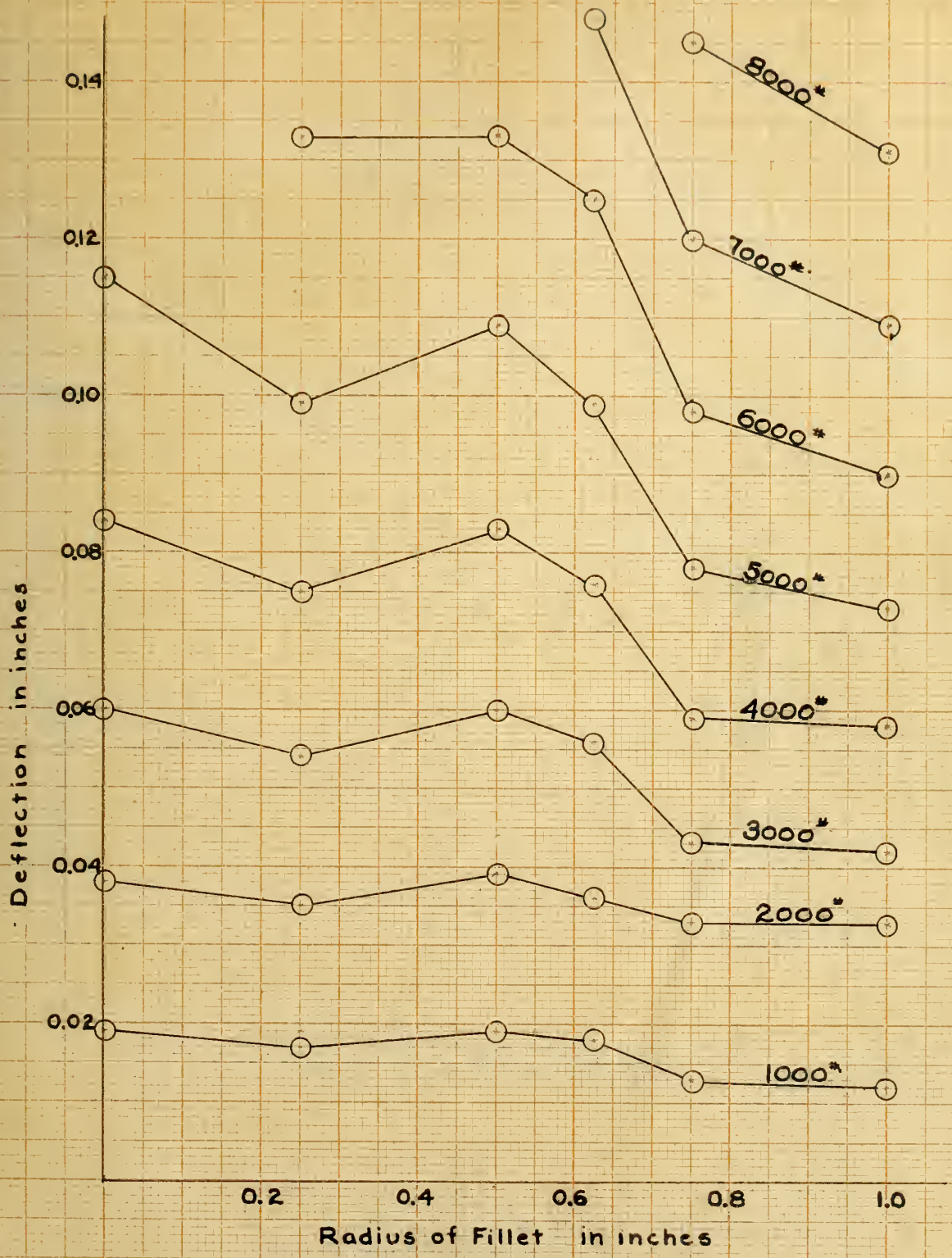

CURVES OF AVERAGE DEFLECTION
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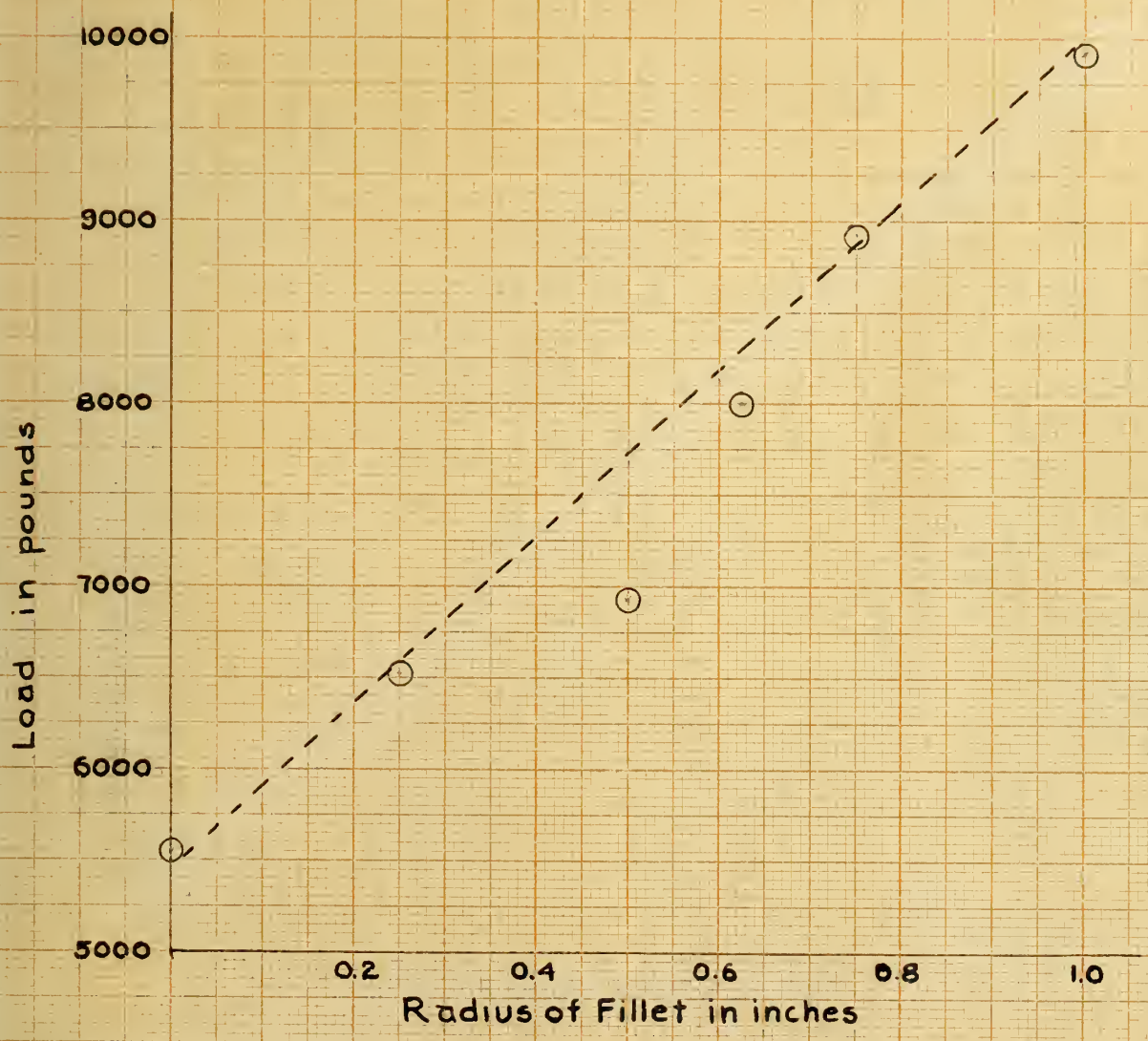

AVERAGE BREAKING LOADS
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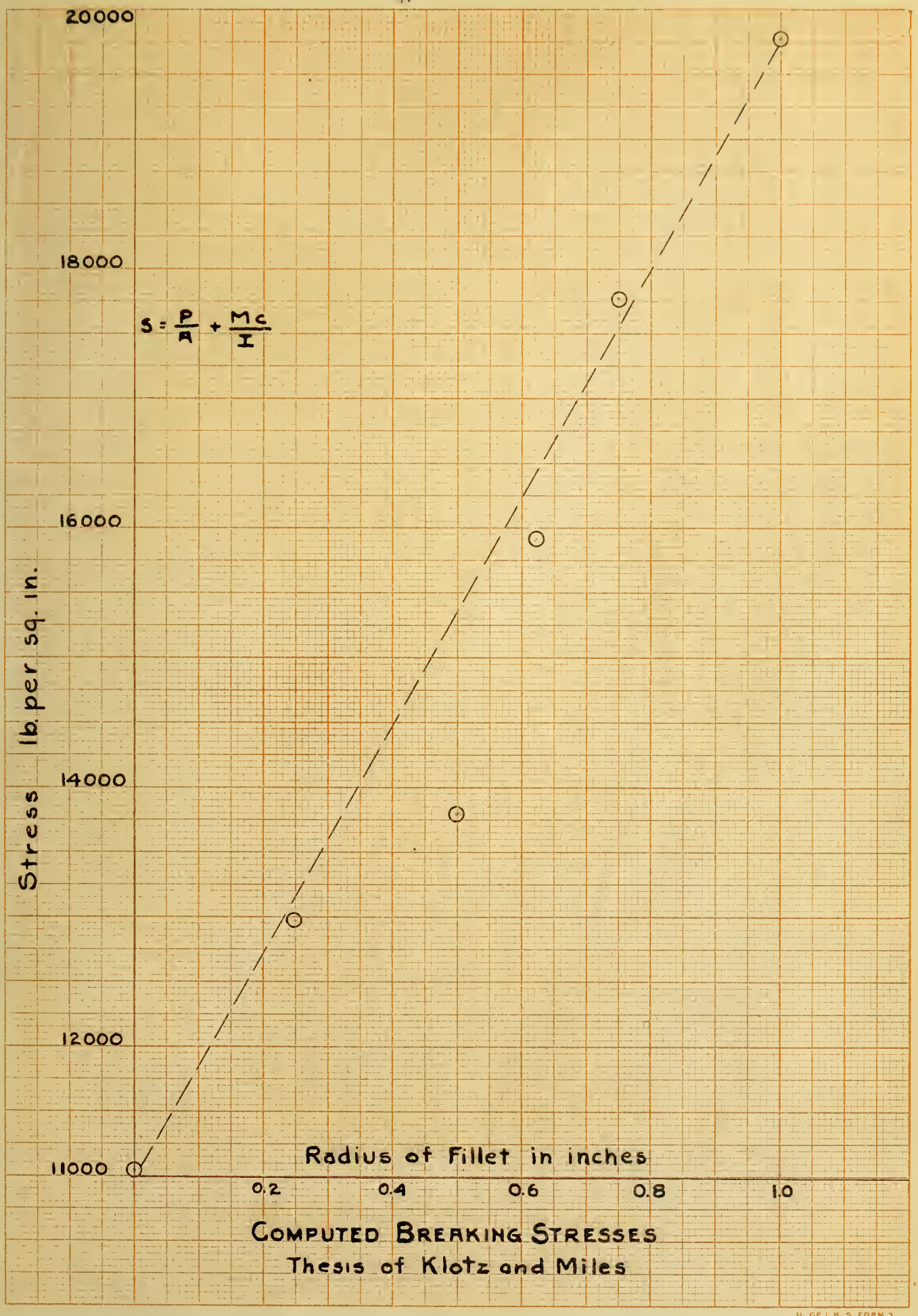
L. C. F. I. G. S. FORM 3



COMPUTED BREAKING STRESSES
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